Comparison of Virtual Reality Versus Physical Reality on Movement Characteristics of Persons With Parkinson’s Disease: Effects of Moving Targets

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Objective: To compare the performance of reaching for stationary and moving targets in virtual reality (VR) and physical reality in persons with Parkinson’s disease (PD).

Design: A repeated-measures design in which all participants reached in physical reality and VR under 5 conditions: 1 stationary ball condition and 4 conditions with the ball moving at different speeds.

Setting: University research laboratory.

Participants: Persons with idiopathic PD (n = 29) and age-matched controls (n = 25).

Interventions: Not applicable.

Main Outcome Measures: Success rates and kinematics of arm movement (movement time, amplitude of peak velocity, and percentage of movement time for acceleration phase).

Results: In both VR and physical reality, the PD group had longer movement time (P < .001) and lower peak velocity (P < .001) than the controls when reaching for stationary balls. When moving targets were provided, the PD group improved more than the controls did in movement time (P < .001) and peak velocity (P < .001), and reached a performance level similar to that of the controls. Except for the fastest moving ball condition (0.5-s target viewing time), which elicited worse performance in VR than in physical reality, most cueing conditions in VR elicited performance generally similar to those in physical reality.

Conclusions: Although slower than the controls when reaching for stationary balls, persons with PD increased movement speed in response to fast moving balls in both VR and physical reality. This suggests that with an appropriate choice of cueing speed, VR is a promising tool for providing visual motion stimuli to improve movement speed in persons with PD. More research on the long-term effect of this type of VR training program is needed.

Key Words: Parkinson disease; Rehabilitation; Task performance and analysis.

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Among the cardinal symptoms of Parkinson’s disease (PD), bradykinesia is considered to have a great negative influence on functional performance in daily life.¹ ² Because daily life is filled with tasks that require rapid aiming movements, interventions to increase movement speed are important for persons with PD.³ Accumulated evidence from neurophysiologic and motor behavior research⁴⁻⁸ has shown that the movement of patients can be improved by external cueing. Commonly provided cues for upper-extremity movement are short presentations of visual or auditory stimuli at the start of the movement.⁹ ¹¹ Recently, several studies¹²⁻¹⁴ used rapidly moving targets as timing cueing and found that persons with PD reached faster when rapidly moving targets were provided than when they reached as fast as possible for stationary objects. It has been suggested¹² that because a rapidly moving target requires that the person reaching for it not only initiate but also properly time the movement, it is more effective than single cueing that primarily prompts the person to begin a movement.

Virtual reality (VR) is defined as “the use of interactive simulations created with computer hardware and software to present users with opportunities to engage in environments that appear to be and feel similar to real world objects and events.”¹⁵(p12) With the advance of technology, VR has been viewed as a potential rehabilitation tool, because it provides a challenging but safe and ecologically valid environment, and at the same time is flexible in stimulus delivery and activity grading.¹⁵ ¹⁶ VR, however, also has some limitations (eg, insufficient depth perception and haptic feedback, and an arbitrary association between vision and action) that may lead to performances different from those in physical reality.¹⁷⁻¹⁸ Performance in VR and physical reality has been compared only for reaching to grasp a stationary object.¹⁸ ¹⁹ and the findings
are inconsistent. Viau et al 16 required subjects to reach for and grasp a virtual ball on a two-dimensional (2-D) computer screen and provided haptic force feedback for grasping the virtual ball. They found longer movement time in VR than in physical reality for both healthy adults and individuals with stroke. Kuhlen et al17 required healthy subjects to reach and grasp an object in a three-dimensional (3-D) virtual environment, with no tactile or force feedback being provided. They found that movement times in VR and physical reality were similar. The different findings between these 2 studies may be related to the VR setup. The absence of depth perception in the 2-D virtual condition may have made the subjects uncertain about the target location, and thus slowed down the movement. The results point to the importance of depth perception in VR for motor control.

VR appears to be a promising tool for offering moving-target cueing for persons with PD, because the controllability of computer-generated conditions in VR allows therapists to easily and precisely manipulate the target’s moving speed and viewing time to make the challenge just right for each participant. In order for therapists to make evidence-based decisions about how to manipulate VR to improve movement in persons with PD, it is important to examine the effect of moving targets in VR. The purpose of this study was to compare the performance of reaching for stationary and moving targets in VR and physical reality in persons with PD. Specifically, we examined whether moving targets in VR would improve movement speed in persons with PD as they would in physical reality. We also wanted to determine if moving targets in VR would benefit more than age-matched controls when reaching for stationary and moving targets. The last hypothesis was formulated because persons with PD, not controls, have impaired internal cueing in the basal ganglia. In addition to movement time, which reflects movement speed, other outcomes (success rate) and kinematic variables were also examined to have a better understanding of participants’ performances.

METHODS

Participants

Based on our pilot study and previous research on the effect of moving targets on reaching, 13,14 a power analysis suggested that 47 participants were needed to yield a power of 80% with the significance criterion set at alpha equal to .05.20 Potential participants with PD were recruited by written invitation and with flyers posted at movement disorder clinics. The control participants were recruited by word-of-mouth invitation within social networks. Those expressing an interest in the study were then contacted by phone and screened for inclusion criteria before the experiment. Inclusion criteria for those with PD were: (1) diagnosed with idiopathic PD, (2) at modified Hoehn & Yahr stages II and III (bilateral symptoms and mild-to-moderate disease severity), (3) stable medication use, (4) between 50 and 75 years old, (5) right-handed by self-report, (6) no serious cognitive deficits (score ≥ 24 on the Mini-Mental State Examination), (7) normal or corrected-to-normal vision and hearing, (8) no history of neurologic conditions other than PD, and (9) no musculoskeletal disorders affecting arm movement. The inclusion criteria for the age-matched controls were identical to criteria (4) through (9) above. Recruitment and testing procedures were in accord with the ethical standards of our medical center and the protocol was approved by our institutional review board. All participants signed an informed consent before the experiment began. Data collection was done from January to October 2009. All participants were compensated for their participation (US $15).

Experimental Tasks

Physical reality. An inclined ramp (length: 200cm; height: 100cm) was built with a barrier placed on its left side. A contact zone (10-cm long) was marked at the right terminal end of the ramp, and participants were required to reach for and grasp the ball (6.5-cm in diameter) in the contact zone (fig 1). Based on pilot work, we inclined the ramp at a 10° angle. From the edge of the barrier to the contact zone, the ramp was 70-cm long. Because the ball was released at different points behind the barrier, the time it took for it to appear from behind the barrier until it reached the contact zone varied: 1.1, 0.9, 0.7, and 0.5 seconds.

Each participant sat in the start position in an armless chair with his or her right hand resting close to the knee on the right thigh. The ramp was placed parallel to the frontal plane of the participant at a distance of 120% of arm length. The upper trunk was not stabilized to allow trunk-assistedprehension. Movement kinematics was recorded by a Patriot® 3-D electromagnetic motion tracking system. Two sensors were used: 1 attached to the sternum and the other to the dorsal surface of the right hand. The sampling rate was 30Hz and latency was less than 18 milliseconds for both sensors simultaneously. The Patriot system is factory calibrated, and, according to the manual, no calibration was needed before data collection. The accuracy and reliability of the Patriot system in our lab was checked and showed an error rate of 0.3% to 0.6% and an intraclass correlation coefficient of 0.97 to 0.99 without metallic interference.

Virtual reality. A projection-based VR system connected with the Patriot system was used. It included a personal computer, a 3-m screen, 2 projectors with high lumens, and polarized glasses. The VR program was designed using the following software: OpenGL (Open Graphics Library), Microsoft Visual C++ 5 and MFC (Microsoft Foundation Class). A virtual ramp identical to the one in physical reality was designed, except that, on the basis of pilot work, a virtual hammer was used to strike the ball (fig 2) and a concrete target to indicate the virtual contact zone. The time from when the ball started moving to when it entered the contact zone was easily manipulated by setting that time in the VR program. The set times were the same as for the real ramp: 1.1, 0.9, 0.7, and 0.5 seconds.

The participant sat in the same place as in the physical reality task. Each participant wore polarized glasses to experience the virtual environment. The VR world was adjusted to locate the virtual contact zone (also indicated by a concrete target) in front of the participant at a distance of 120% of arm length. As in physical reality conditions, sensors of the Patriot system were attached to the right hand to detect hand motion and to the sternum to detect trunk motion. The images on the screen were set up so that the participant could see the ramp in the middle of the screen and a virtual right hand on the bottom of the screen. The movement of the virtual hand corresponded to the participant’s own hand movements.
Forward leaning of the trunk produced changes of the virtual world centered about the viewpoint.

Study Design and Procedures

A repeated-measures design was used. All participants performed the experimental task in physical reality first and, after a 10-minute break, then in VR. In each context, the participant was required to reach for and grasp a tennis ball with the right hand under 5 conditions: the ball was stationary in 1 condition and moving in 4. In the stationary condition, the participant was required to reach as fast as possible to grasp the ball placed in the contact zone. The stationary ball condition was done first and then, in random order, the moving ball conditions. The participants did 1 practice trial and 5 test trials for each cueing condition in physical reality and 3 practice trials and 5 test trials for each cueing condition in VR. The participants required more practice trials to get used to the VR scenes and tasks. The number of practice trials was decided on based on participants’ self-reports in a pilot study. Kinematic data from the practice trials were not included in the analysis. An average value over the 5 test trials was used in data analysis no matter whether the trial was successful or not.

Dependent Measures

The success rate for the moving ball conditions was computed. In physical reality, a trial was considered successful if the participant touched and stopped the moving ball in the contact zone. In VR, a trial was considered successful when the distance between the participant’s hand sensor (placed in the dorsal side) and the center of the ball was between 5.75 and 8.75 cm (the radius of the ball + thickness of the hand and sensor ± 1.5 cm error range) in the contact zone.

For kinematic measures, velocity was derived from position data that were filtered using a moving-average filter. The cutoff value to define movement onset was set at 5% of peak velocity. End of movement of a successful trial in VR was defined as the time when the computer detected a successful catch; end of movement of unsuccessful VR trials and all trials in physical reality was set at 5% of peak velocity. Switches were not used to measure movement onset or offset because metal in a switch might have interfered with the transmission of the Patriot’s electromagnetic signals.

This study included the following kinematic variables to characterize speed, forcefulness, and strategy of arm movement: movement time, amplitude of peak velocity, and percentage of total movement time represented by the acceleration phase (PTA). Movement time is the duration of execution of arm movement. A faster movement would have a shorter movement time. Peak velocity is the highest instantaneous velocity during the arm movement. The higher the peak velocity, the more forceful the movement. When the hand reaches for a target, it generally

Fig 1. Experimental setup for (A) physical reality and (B) virtual reality.

Fig 2. Screen presentation of the virtual reality task. (A) A hammer to strike the ball to start a trial. (B) The ball rolling down the ramp. (C) The participant reaching for the ball.
first accelerates toward the target and then decelerates to correct the trajectory. The deceleration phase is believed to be used to process feedback information and to adjust movement trajectory.26 A movement with a longer deceleration phase (ie, a lower PTA) is considered to reflect a more guided, feedback-dependent strategy.27

### Statistical Analysis

The stationary ball condition was regarded as the baseline measure of the participant’s maximum reaching speed. The success rate in baseline was 100% and was excluded from analysis. To test the first hypothesis, a mixed 2-way analysis of variance (ANOVA) with 1 between factor (group: PD vs controls) and 1 within factor (context: VR vs physical reality) was used to analyze performance when the participants reached for stationary balls. For the second hypothesis, a mixed 3-way ANOVA with an additional within factor (moving ball speed in terms of target viewing time [cueing]: 1.1 vs 0.9 vs 0.7 vs 0.5s) was used to analyze performance when the participants reached for moving balls. Finally, for the third hypothesis regarding the joint effects of group, context, and cueing on the change of performance between the stationary (baseline) and each moving ball condition, another mixed 3-way ANOVA was used. The change score for each moving ball condition was computed as the difference in performance between that moving ball condition and the stationary ball condition. Performance in the baseline condition (reaching for a stationary ball) was not used as a covariate in the analysis, because reaching for a stationary ball is conceptually different from reaching for a moving ball (self-initiated vs externally-cued), and we did not expect correlations between reaching for a stationary ball and change of performance in response to a moving ball.

All statistical analyses were done using SPSS 17.0.49 Pairwise comparisons using Fisher least significant difference tests were used for post hoc analyses for effects with statistical significance (α=0.05). By first performing the overall ANOVA and comparing only the pairs of means with the least significant difference procedure if the overall ANOVA was statistically significant, we have protected ourselves to some extent from the multiple-comparisons problem.28 For the effect size, index eta-squared (η²) was used. As a rule of thumb, an eta-squared of 0.01 indicates a small effect, 0.06 a medium effect, and 0.14 a large effect.29

### RESULTS

#### Participant Characteristics

The PD group consisted of 13 women and 16 men with a mean age ± SD of 66.17±8.26 years and a mean duration of PD ± SD of 5.46±3.94 years. Of these participants, 26 were at Hoehn & Yahr stage II, and 3 at stage III. For the age-matched controls (14 women and 11 men; mean age ± SD, 65.40±5.78y), their sex distribution and age were not significantly different from those of the participants with PD (sex: χ²=0.67, P=0.413; age: t=0.39, P=0.70). Participants reported no prior experience with VR or computer gaming.

#### Reaching for Stationary Targets

Table 1 and figure 3 show the participants’ performance in the stationary and moving ball conditions in VR and physical reality. Normality was checked using a Q-Q plot, which showed no strong evidence against the normality assumption. Two-way ANOVA showed no significant group × context interaction effect for any dependent variables. A significant group effect was found for movement time (F1,52=29.34, P<0.001, η²=0.36) and peak velocity (F1,52=18.69, P<0.001, η²=0.26). In the stationary ball condition, the PD group had longer movement time and lower peak velocity than the controls. A significant context effect was found for peak velocity (F1,52=5.21, P=0.027, η²=0.09) and PTA (F1,52=4.18, P=0.046, η²=0.07). All participants had lower peak velocity and a relatively longer deceleration phase in VR than in physical reality.

### Table 1: Descriptive Data for Reaching Performance in the Experimental Conditions

<table>
<thead>
<tr>
<th>Dependent Variables</th>
<th>Context</th>
<th>Condition</th>
<th>1.1s</th>
<th>0.9s</th>
<th>0.7s</th>
<th>0.5s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Success rate</td>
<td>PD group</td>
<td>Physical 1</td>
<td>0.98±0.06</td>
<td>0.99±0.08</td>
<td>0.93±0.13</td>
<td>0.69±0.30</td>
</tr>
<tr>
<td></td>
<td>PD group</td>
<td>Virtual 1</td>
<td>0.81±0.34</td>
<td>0.77±0.32</td>
<td>0.63±0.36</td>
<td>0.25±0.34</td>
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<tr>
<td></td>
<td>Control group</td>
<td>Physical 1</td>
<td>0.99±0.04</td>
<td>1.00±0.00</td>
<td>0.98±0.05</td>
<td>0.90±0.13</td>
</tr>
<tr>
<td></td>
<td>Control group</td>
<td>Virtual 1</td>
<td>0.77±0.35</td>
<td>0.74±0.32</td>
<td>0.66±0.34</td>
<td>0.26±0.35</td>
</tr>
<tr>
<td>Movement time (s)</td>
<td>PD group</td>
<td>Physical 0.78±0.18</td>
<td>0.81±0.09</td>
<td>0.76±0.10</td>
<td>0.61±0.09</td>
<td>0.45±0.06</td>
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<tr>
<td></td>
<td>PD group</td>
<td>Virtual 0.76±0.13</td>
<td>0.87±0.15</td>
<td>0.75±0.10</td>
<td>0.62±0.07</td>
<td>0.51±0.08</td>
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<tr>
<td></td>
<td>Control group</td>
<td>Physical 0.58±0.13</td>
<td>0.79±0.16</td>
<td>0.72±0.10</td>
<td>0.60±0.06</td>
<td>0.44±0.06</td>
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<tr>
<td></td>
<td>Control group</td>
<td>Virtual 0.57±0.10</td>
<td>0.82±0.16</td>
<td>0.73±0.13</td>
<td>0.57±0.10</td>
<td>0.44±0.05</td>
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<td>Peak velocity (cm/s)</td>
<td>PD group</td>
<td>Physical 153.41±33.81</td>
<td>128.78±21.12</td>
<td>139.58±22.93</td>
<td>164.90±28.79</td>
<td>223.25±24.70</td>
</tr>
<tr>
<td></td>
<td>PD group</td>
<td>Virtual 147.79±36.21</td>
<td>129.24±25.79</td>
<td>143.39±25.81</td>
<td>170.88±23.55</td>
<td>204.78±28.64</td>
</tr>
<tr>
<td></td>
<td>Control group</td>
<td>Physical 199.09±43.52</td>
<td>135.26±31.66</td>
<td>145.16±27.26</td>
<td>163.74±25.22</td>
<td>243.68±35.31</td>
</tr>
<tr>
<td></td>
<td>Control group</td>
<td>Virtual 189.69±33.86</td>
<td>132.77±36.00</td>
<td>146.41±39.87</td>
<td>176.81±37.26</td>
<td>223.36±35.46</td>
</tr>
<tr>
<td>PTA (%)</td>
<td>PD group</td>
<td>Physical 40.72±9.87</td>
<td>54.55±15.24</td>
<td>49.86±12.83</td>
<td>48.25±10.87</td>
<td>48.01±10.36</td>
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<td></td>
<td>PD group</td>
<td>Virtual 36.48±7.48</td>
<td>41.03±8.14</td>
<td>39.04±11.17</td>
<td>35.31±8.62</td>
<td>37.23±7.39</td>
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<tr>
<td></td>
<td>Control group</td>
<td>Physical 38.31±10.17</td>
<td>49.65±13.12</td>
<td>49.21±12.02</td>
<td>39.99±11.33</td>
<td>42.81±11.85</td>
</tr>
<tr>
<td></td>
<td>Control group</td>
<td>Virtual 36.12±7.50</td>
<td>49.36±14.19</td>
<td>40.12±11.96</td>
<td>39.43±10.93</td>
<td>38.88±7.10</td>
</tr>
</tbody>
</table>

NOTE. Values are means ± SD.
Reaching for Moving Targets

For the moving ball conditions, 3-way ANOVA indicated no significant group × context × cueing effect for any variables. For success rate (see fig 3A), a significant context effect (F₁,₅₂=86.43, P<0.001, η²=0.62), a cueing speed effect (F₃,₁₅₆=73.64, P<0.001, η²=0.66 for a linear trend), and a context × cueing interaction effect (F₃,₁₅₆=24.19, P<0.001, η²=0.41 for a linear trend) were found. Post hoc analysis revealed that for both VR and physical reality, the success rate was significantly lower in the faster cueing conditions. The success rate was significantly lower in VR than in physical reality, and the discrepancy was larger at faster speeds.

Because of technical problems with the Patriot system, the kinematic data of 1 participant with PD were missing. For movement time (see fig 3B) and peak velocity (see fig 3C), a significant cueing effect (movement time: F₃,₁₅₃=317.11, P<0.001, η²=0.92 for a linear trend; peak velocity: F₃,₁₅₃=346.66, P<0.001, η²=0.92 for a linear trend) and a context × cueing interaction effect (movement time: F₃,₁₅₃=4.15, P<0.01, η²=0.23 for a quadratic trend, η²=0.02 for a linear trend; peak velocity: F₃,₁₅₃=15.12, P<0.001, η²=0.33 for a quadratic trend, η²=0.13 for a linear trend) were found. Post hoc comparisons indicated that for both VR and physical reality, movement time was significantly shorter and peak velocity was higher in the faster cueing conditions. Movement time was significantly longer in VR than in physical reality for the 1.1- and 0.5-second conditions. Peak velocity was significantly higher for the 0.7-second condition and lower for the 0.5-second condition in VR than in physical reality.

For PTA (see fig 3D), a significant context effect (F₁,₅₁=44.63, P<0.001, η²=0.47), a cueing effect (F₃,₁₅₃=14.61, P<0.001, η²=0.33 for a linear trend), and a group × context effect (F₁,₅₁=13.40, P=0.001, η²=0.21) were found. Faster cueing conditions elicited lower PTAs, which meant a relatively longer deceleration phase to locate the target position. Further analysis showed a significant context effect in the 1.1-, 0.7-, and 0.5-second conditions for the PD group, but not for the controls. Generally, PTA was lower in VR than in physical reality for the PD group, but not for the controls.

Change in Performance Between Stationary and Moving Targets

ANOVA (group × context × cueing) on the change of performance between the moving and stationary ball conditions showed results similar to those in the reaching for...
moving targets, except that a significant group effect (movement time: \( F_{1,51} = 16.18, P < 0.001, \eta^2 = 0.24 \); peak velocity: \( F_{1,51} = 18.60, P < 0.001, \eta^2 = 0.27 \)) was found for movement time and peak velocity. With moving targets, the PD group showed significantly more improvement and less deterioration in movement time and peak velocity than the control group.

**DISCUSSION**

We provided stationary target objects as well as targets moving at different speeds in VR and physical reality for individuals with PD and for age-matched controls. Our hypotheses were generally supported. First, we found that in both VR and physical reality, the PD group had longer movement time and lower peak velocity than the control group when reaching for a stationary ball at a self-determined maximum speed. Second, for both VR and physical reality, movement time was significantly shorter and peak velocity was higher in the faster cueing conditions. Third, when moving targets were provided, the PD group showed more improvement than the control group in movement time and peak velocity, thus reaching a performance level similar to that of the control group. However, the effect of cueing speed was context dependent. While most cueing conditions in VR elicited performances generally similar to those in physical reality, the 0.5-second moving ball elicited longer movement time and lower peak velocity in VR than in physical reality. Finally, the PD group had a lower PTA in VR than in physical reality, which suggested that the PD group was more feedback dependent in VR than in physical reality.

We compared performances between VR and physical reality when the participants reached for stationary objects and found that the reaching movement was less forceful (lower peak velocity) and more feedback dependent (lower PTA) in VR than in physical reality. Our results are consistent with the findings of Kuhlen et al., but not with the findings of Viau et al. Kuhlen found that when reaching to grasp stationary objects, healthy adults had similar movement time but lower peak velocity in VR than in physical reality. Viau reported that healthy adults and individuals with stroke had longer movement time in VR than in physical reality. Kuhlen used a 3-D display for VR with no haptic feedback, which is similar to our study, while Viau used a 2-D display with haptic feedback. The findings suggest that a 3-D display with some depth perception to indicate movement amplitude is important for movement time. In addition, the lower peak velocity in VR may be due to a lack of haptic feedback to sense the weight of the object, and thus movement was less forceful in this study and the Kuhlen study.

In addition to the stationary ball condition, we provided target objects moving at different speeds to challenge the visuomotor ability of persons with PD. As cueing became faster, the success rate fell, movement time shortened, peak velocity rose, and PTA fell. The moving-target cueing resulted in more improvement in movement time and peak velocity in the PD group than in the control group, and thus the PD group performed similarly to the control group in the moving ball conditions in terms of movement speed and forcefulness. The results of the cueing speed effect are generally in agreement with previous studies that tested persons with PD in physical reality. Our study extends previous findings by showing that moving targets affected movement not only in physical reality but also in VR. Previous studies have identified cortical areas in humans that respond selectively to rapid visual motion cues. It is suggested that visual motion stimuli engage neural circuits that are less affected by PD, and thus allow persons with PD to make fast movements in response to a rapidly moving target in physical reality. Our findings suggest that persons with PD are also sensitive to virtual visual-motion stimuli, despite the limitations of VR, such as inconsistent accommodation and convergence.

Our findings have implications for motor control theories. According to the dynamic systems theory, movement patterns emerge from the interplay of person, task, and environmental constraints. Our study provides evidence to support the theory by showing complex interactions between the person (PD vs controls), task (reaching for stationary vs moving balls), and environment (VR vs physical reality). Moreover, our findings of different performance patterns between VR and physical reality provide insight in relation to perception-action coupling in motor control theories. Catching an object is a complex perception-action skill that requires visual observation of the object and one’s own hand during the catching. VR, however, changes perception-action coupling in 2 ways. First, the insufficient depth perception in VR makes it difficult to precisely locate the target position. Second, the performer in VR obtains visual feedback of his or her hand movement by watching the virtual hand on the screen. The different perception experience in VR may interfere with the estimate of time-to-contact between the virtual ball and virtual hand, and may subsequently affect the action. As a result, participants, especially those with PD, used a more guided and feedback-dependent movement strategy (lower PTA) in VR than in physical reality.

Further, in the coordination of vision and movement, a certain amount of time is required to use visual feedback to make movement corrections while the movement is in progress. Although the amount of time to process visual feedback was generally estimated to be between 0.10 and 0.16 seconds, it is likely that the minimum amount of time required is longer in VR because of the indirect perception-action coupling. Therefore, the success rate fell in the VR 0.5-second condition because the time was too short to allow a successful catch. The difficulty of successfully catching the virtual ball in 0.5 seconds may in turn adversely affect the participants’ performance, as reflected in prolonged movement time and decreased peak velocity. The results point to the importance of investigating the minimum amount of time required for persons with PD to make vision-based movement corrections when doing VR tasks.

From the perspective of motor learning that the PD group used a more guided strategy to reach for moving balls in VR than in physical reality may suggest that VR presents a new learning situation for the PD group, and thus those participants were in the early stages of motor learning. Persons with PD have been reported to have a slower rate of motor learning than those without PD. Therefore, it is likely that the number of our practice trials for the VR tasks was not enough for the participants with PD to move into the autonomous stage of learning. While the results suggest that more practice is needed for persons with PD to become familiar with VR open tasks, it is important for future research to examine whether the movement strategy in persons with PD would become more automatic and less guided with practice using VR.

This study contributes to the field of rehabilitation by providing evidence about how to manipulate task and environmental constraints to improve movement in persons with PD. Specifically, this study shows how to manipulate VR scenarios to improve movement speed in persons with PD, while at the same time depicting their movement characteristics in VR. Our results suggest that VR tasks that require participants to reach for fast moving targets did improve movement speed in persons with PD, but some caveats are needed. First, VR is likely to...
induce a more guided movement strategy than physical reality, and thus therapists should manipulate task and environmental constraints according to the treatment goal (eg, to improve movement speed or to induce an automatic strategy). Second, because the amount of time required for vision-based movement corrections is longer in VR than in physical reality, the target viewing time in VR has to be longer than in physical reality for participants to successfully catch the target.

Study Limitations

This study has some limitations. We recruited a convenience sample, and thus our results may be threatened by the bias of self-selection. In addition, although we found the expected condition effects, this study’s small-to-moderate sample size may somehow limit its statistical conclusion validity and external validity. Future research with a larger sample size is needed to increase the sensitivity of testing the assumptions underlying the statistical analyses to allow the use of more rigorous tests, such as multivariate ANOVAs, and to increase the generalizability of our findings. Moreover, although we aimed at matching the conditions in VR to those in physical reality, we provided a virtual hammer to signal the start of a trial and a concrete target to indicate the virtual contact zone on the basis of our pilot work. However, the results suggest that even with these compensations, our participants still had difficulty catching fast-moving balls in VR. Future work is needed to improve the VR system by improving the sense of immersion, depth perception, and haptic feedback.34

Another limitation of this study may be that we did not balance the testing order and let all participants complete the physical reality conditions first and then the VR conditions. This testing order was decided in view of the fact that most people engage in activities in physical reality most of the time and move to VR activities only some of the time. Therefore, doing physical reality conditions first would avoid the possible carryover effect of VR to physical reality and obtain performance similar to that in physical reality. In our design, the carryover effect of physical reality to VR could be washed out by the break and the practice trials. If not, the residual carryover effect that physical reality might have on VR activities represents a possible influence that we may face in clinics when people move from physical reality to VR activities. To examine the possible carryover effect from 1 context to another, future research may repeat each context twice, as in the A-B-A-B type of a single-subject design.

Finally, this study examined only motor performance in response to real and virtual moving target objects. It has been reported13 that cueing helps persons with PD improve motor performance, and cueing effects were retained immediately after cue withdrawal. Although the carry-over effect of longer periods of cued training is not well-established, overall, the literature suggests that the acquisition of motor learning may be greater in persons with PD when it becomes associated with external cueing. Therefore, future research should focus on the long-term effect of VR training that incorporates target objects moving at appropriate speeds and examines whether the motor skills practiced in VR transfer to physical reality.

CONCLUSIONS

Persons with mild-to-moderate PD reached for a stationary object more slowly than age-matched controls at self-determined maximum speeds. When moving targets were provided, persons with PD increased their movement speed to a level similar to that of controls. A moving target increased movement speed not only in physical reality but also in VR. Our study extends the previous findings of the moving target effect in physical reality to VR. Our findings suggest that with an appropriate choice of cueing speed, VR is a promising tool for offering visual motion stimuli to increase movement speed in persons with PD. Research is needed to examine the long-term effect of VR training that incorporates target objects moving at appropriate speeds.

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Suppliers

a. Polhemus Inc, 40 Hercules Dr, Colchester, VT 05446-0560.
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Trunk–arm coordination in reaching for moving targets in people with Parkinson’s disease: Comparison between virtual and physical reality

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Abstract

We used a trunk-assisted prehension task to examine the effect of task (reaching for stationary vs. moving targets) and environmental constraints (virtual reality [VR] vs. physical reality) on the temporal control of trunk and arm motions in people with Parkinson’s disease (PD). Twenty-four participants with PD and 24 age-matched controls reached for and grasped a ball that was either stationary or moving along a ramp 120% of arm length away. In a similar VR task, participants reached for a virtual ball that was either stationary or moving. Movement speed was measured as trunk and arm movement times (MTs); trunk–arm coordination was measured as onset interval and offset interval between trunk and arm motions, as well as a summarized index—desynchrony score. In both VR and physical reality, the PD group had longer trunk and arm MTs than the control group when reaching for stationary balls (p < 0.001). When reaching for moving balls in VR and physical reality, however, the PD group had lower trunk and arm MTs, onset intervals, and desynchrony scores (p < 0.001). For the PD group, VR induced shorter trunk MTs, shorter offset intervals, and lower desynchrony scores than did physical reality when reaching for moving balls (p < 0.001). These findings suggest that using real moving targets in trunk-assisted prehension tasks improves the speed and synchronization of trunk and arm motions in people with PD, and that using virtual moving targets may...
induce a movement termination strategy different from that used in physical reality.

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1. Introduction

Parkinson’s disease (PD) is a progressive neurodegenerative disorder associated with basal ganglia dysfunction, which causes impairments in the temporal regulation of movements (Delwaide & Gonce, 1993; Wang, Bohan, Leis, & Stelmach, 2006). Research has reported that movements in people with PD become increasingly slow when doing tasks involving long sequences or different movement components (Agostino, Berardelli, Formica, Accornero, & Manfredi, 1992; Benecke, Rothwell, Dick, Day, & Marsden, 1987a, 1987b). The observed movement slowness results from not only the prolonged movement time of individual movement components (e.g., reach and grasp), but also the delay between movement components, which suggests impaired ability in the timing and coordination of individual components (Bennett, Marchetti, Iovine, & Castiello, 1995; Castiello, Stelmach, & Lieberman, 1993).

However, relatively little attention has been given to the coordination of different body segments (e.g., trunk and arm) in people with PD. In daily life, people are confronted with situations in which an object is located beyond arm’s reach; therefore, to extend the reach distance, the trunk becomes involved in the reach to the target (Wang & Stelmach, 2001). Limited research on trunk–arm coordination in PD showed that in trunk-assisted prehension tasks, people with PD had longer onset and offset intervals between trunk and arm motions than did healthy controls (Poizner et al., 2000; Wang et al., 2006). These results suggest that, while healthy adults coordinate the trunk and arm movements as a single unit, people with PD do not coordinate these movements in the same manner. Slowed movement and segmented trunk–arm coordination restrict the ability to efficiently reach beyond arm’s length and thus have a negative influence on functional performance in daily life (Alves, Forsaa, Pedersen, Dreetz Gjerstad, & Larsen, 2008; Muslimovic et al., 2008). A significant part of rehabilitation for people with PD is to improve movement speed and synchronization. Understanding the temporal control of trunk–arm coordination in response to task and environmental constraints may provide insight into the underlying control processes and would help shape treatment strategies for rehabilitation.

Dynamic systems theory proposes that movement patterns emerge from the interplay of personal, task, and environmental constraints (Newell, 1986). This framework provides a guideline for rehabilitation practitioners to analyze performance and to manipulate constraints in order to influence movement patterns (Newell & Valvano, 1998). A potentially important task constraint is the status of the objects involved: whether they are stationary or in motion (Gentile, 1987; Magill, 2011). Healthy adults are sensitive to a target’s motion and use characteristics of the target’s motion when generating their own movements (Carnahan & McFadyen, 1996; Mason & Carnahan, 1999). For people with PD, a moving target provides visual motion stimuli that may serve as an external trigger and compensate for the impaired internal timing cueing caused by basal ganglia dysfunction. Some studies examined the effect of fast-moving targets on the kinematics of reach and grasp (Majsak, Kaminski, Gentile, & Flanagan, 1998; Majsak, Kaminski, Gentile, & Gordon, 2008; Schenk, Baur, Steude, & Botzel, 2003). Their results indicated that a moving target improved the speed of reaching movement in participants with PD to a level similar to that in healthy controls (Majsak et al., 1998, 2008). Except for the grasping component, the movement speed in participants with PD was only slightly improved by the moving target, and it remained impaired compared with controls (Schenk et al., 2003). Considering the differential effects of moving targets on different movement components, it is important to examine whether and to what degree moving targets improve the speed and synchronization of trunk and arm motions during trunk-assisted prehension tasks in people with PD.

Newly developed virtual reality (VR) technology provides a channel for examining the influence of environmental constraints. VR has garnered growing attention for its promising applications in research and clinical practice. The controllability of the computer-generated conditions in VR allows...
researchers to easily and precisely manipulate experimental scenarios for specific investigations (Dvorkin, Shahar, & Weiss, 2006). As a rehabilitation tool, VR provides a challenging but safe and ecologically valid environment, and at the same time is flexible in stimulus delivery and activity grading (Keshner, 2004; Weiss & Katz, 2004). However, VR also has limitations. Its insufficient depth perception and lack of haptic feedback may lead to movement patterns different from those in physical reality (Martin, Julian, Boissieux, Gascael, & Prablanc, 2003; Viau, Feldman, McFadyen, & Levin, 2004). Performance in VR and physical reality has been compared only for pointing movements (Knaut, Subramanian, McFadyen, Bourbonnais, & Levin, 2009) and for reaching to grasp a stationary object (Kuhlen, Kraiss, & Steffan, 2000; Viau et al., 2004). Generally, these studies indicated that the changed perception of the target location in space may result in slower and less accurate movement in VR. To the best of our knowledge, there is no published research on examining trunk–arm coordination in reaching for virtual moving targets. Given the trend of the increasing use of VR in clinics, it is important to analyze movement in VR in detail instead of assuming that VR and physical reality are essentially similar. Moreover, examining trunk–arm coordination in response to virtual moving targets provides information for rehabilitation practitioners to make evidence-based decisions about the use of VR to improve the speed and synchronization of trunk and arm motions in people with PD.

Therefore, the purpose of this study was to (a) examine the effect of moving targets on the temporal control of trunk and arm motions, and (b) compare the movement between VR and physical reality in people with PD when reaching for stationary and moving targets. Neurologically intact adults (controls) were included to provide a basis for establishing typical patterns of task performance in different experimental conditions. We hypothesized that reaching for moving targets would be faster and more synchronized than reaching for stationary targets in people with PD. In addition, considering the insufficient depth perception in VR, which may compound the difficulty of locating moving targets, we hypothesized that VR would induce movement patterns different from those in physical reality in people with PD when reaching for moving targets.

2. Methods

2.1. Study design

A repeated-measures design was used. Each participant performed a trunk-assisted prehension task in physical reality first and then in VR. In each context, the participant was required to reach and grasp a tennis ball with the right hand under two conditions: (a) stationary ball condition: reach as fast as possible to grasp a ball placed in the contact zone, and (b) moving ball condition: reach to grasp a moving ball from within the contact zone. The stationary ball condition was done first and then the moving ball condition.

2.2. Participants

Based on our pilot studies (Ma et al., 2011; Wang et al., 2011) and previous research (Majsak et al., 1998, 2008) on the effect of moving targets on reaching, a power analysis suggested that 47 participants were needed to yield a power of 80% with the significance criterion set at \( \alpha = 0.05 \) (Cohen, 1988). Potential participants with PD were recruited by written invitation and with flyers posted at movement disorder clinics. The control participants were recruited by word-of-mouth invitation within social networks. Inclusion criteria for those with PD were: (a) diagnosed with idiopathic PD, (b) at Hoehn & Yahr stage (Hoehn & Yahr, 1967) I, II, or III, (c) stable medication use, (d) between 50 and 75 years old, (e) right handedness by self-report, (f) no serious cognitive deficits (score \( \geq 24 \) on the Mini-Mental Status Examination [MMSE]) (Folstein, Folstein, & McHugh, 1975), (g) normal or corrected-to-normal vision and hearing, (h) no history of neurological conditions other than PD, and (i) no musculoskeletal disorders affecting arm movement. The inclusion criteria for the age-matched controls were identical to criteria (d)–(i) above. All participants signed informed consent forms approved by our Institutional Review Board.

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2.3. Procedures

Each participant sat in the start position in an armless chair with their right hand resting close to the knee on their right thigh. For the conditions in physical reality (Fig. 1), an inclined ramp (length: 200 cm; height: 100 cm) was placed parallel to the frontal plane of the participant at a distance equal to 120% of arm length. On the left side of the ramp was a barrier that allowed the experimenter to release the ball from behind the barrier. A contact zone (10 cm long) was marked at the right terminal end of the ramp, and the participant was required to reach for and grasp the ball in the contact zone. The height and position of the ramp was set so that the contact zone was in front of the right shoulder at chest level.

Based on pilot work, we set the time constraint in the moving ball condition as 0.7 s, which was the time it took for the ball to appear from behind the barrier until it arrived at the contact zone, to challenge the movement speed while keeping a satisfactory success rate in people with PD. Each participant did three practice trials and five test trials under each condition. The participants with PD were tested in the “on” medication state. All participants with PD performed the experimental conditions without apparent dyskinesia interfering with their movement.

Movement kinematics was recorded by an electromagnetic motion tracking system (Patriot; Polhemus Inc., Colchester, VT, USA). Two sensors were used: one attached to the sternum and the other to the dorsal surface of the right hand. The sampling rate was 30 Hz and latency was less than 18 ms for both sensors simultaneously. Kinematic data from the practice trials were not included in the analysis.

For the VR part, the participant sat in the same place as in the physical reality conditions (Fig. 1). A projection-based VR system connected with the Patriot system was used to provide the VR conditions. Each participant wore polarized glasses to experience the virtual environment. The VR world was adjusted to locate the virtual contact zone (also indicated by a concrete target) in front of the participant at a distance of 120% of arm length. As in the physical reality conditions, sensors of the Patriot system were attached to the sternum to detect trunk motion and to the right hand to detect hand motion.

A virtual ramp was designed to be identical to the real ramp, except that, on the basis of pilot work, a virtual hammer was used to strike the ball and a concrete target was used to indicate the virtual contact zone. The images on the screen were set up so that the participant could see the ramp in the middle of the screen and a virtual right hand on the bottom of the screen. The movement of the virtual hand corresponded to the participant’s own hand movements. Forward leaning of the trunk produced changes of the virtual world centered about the viewpoint. When a participant successfully caught the ball, the ball would move with the participant’s hand for 2 s, as it would have had the participant actually lifted the ball from the contact zone. The conditions, instructions, and number of trials were similar to those in physical reality.

2.4. Outcomes

The recorded data of the sensors attached to the sternum and hand were used to compute the trunk and arm tangential-velocity profiles. To characterize temporal control of trunk and arm motions, this study included the following variables: trunk movement time (MT), arm MT, onset interval, offset interval, and desynchrony scores. The cutoff value to define movement onset and offset was set at 5% of peak velocity. MT is the duration of execution of movement. Trunk/arm MT was defined as the duration from the onset to the offset of the trunk/arm motion. To calculate the onset and offset intervals, the absolute values of the time interval between the onset and offset of trunk and arm motions were obtained from each test trial of each participant. The desynchrony score represents the duration of only one of the trunk and arm motions relative to the overall movement duration (Wang et al., 2006). It was calculated as the sum of onset and offset intervals divided by total movement duration, which was defined as the interval from the time when the first segment moves (either trunk or arm) to the time when last segment stops moving.

2.5. Statistical analysis

To test the hypotheses, a mixed 3-way analysis of variance (ANOVA) with one between factor (group: PD vs. controls) and two within factors (task: stationary vs. moving ball; context: VR vs.
Fig. 1. Experimental setup for physical reality conditions (upper panel) and VR conditions (lower panel).
physical reality) was used to analyze participant performance. All statistical analyses were done using
SPSS 17.0 (SPSS Inc., Chicago, IL, USA). Pair-wise comparisons using Fisher’s least significant difference
(LSD) tests were used for post hoc analyses for effects with statistical significance ($p = 0.05$). The LSD
procedures were used because there were only two groups and only specific comparisons of interest
were intended. By first performing the overall ANOVA, and comparing only pairs of means with the
LSD procedure if the overall ANOVA was statistically significant, we have protected ourselves to some
extent from the multiple-comparisons problem (Rosner, 2006). For effect size, index eta-squared ($\eta^2$)
was used. As a rule of thumb, an $\eta^2$ of .01 indicates a small effect, of .06 a medium effect, and of .14 a
large effect (Cohen, 1988).

3. Results

3.1. Participant characteristics

We enrolled a sample of convenience composed of 24 people with PD and 24 healthy
age-matched controls. Table 1 shows the demographic and clinical characteristics of the participants
with PD. The PD group consisted of 11 women and 13 men (mean age: 65.75 ± 6.82 years old;
mean duration of PD: 5.15 ± 3.89 years), 3 of whom were at Hoehn & Yahr stage I, 12 at stage II,
and 9 at stage III. Total Daily Levodopa Equivalent Dose (Tomlinson et al., 2010) was also calculated
for each participant with PD. The gender distribution and mean age of the controls (11 women and
13 men; 65.67 ± 5.75 years old) were not significantly different from those of the participants with
PD.

<table>
<thead>
<tr>
<th>ID</th>
<th>Gender</th>
<th>Age (year)</th>
<th>Duration of PD (year)</th>
<th>Cardinal symptoms</th>
<th>H&amp;Y stage in “on” state</th>
<th>Total L-dopa equivalent dose (mg/day)</th>
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<td>1</td>
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<td>71</td>
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<td>Tremor, postural instability</td>
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<td>857</td>
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<tr>
<td>2</td>
<td>M</td>
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</tr>
<tr>
<td>4</td>
<td>M</td>
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<tr>
<td>7</td>
<td>F</td>
<td>68</td>
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</tr>
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<td>68</td>
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<tr>
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<td>69</td>
<td>8</td>
<td>Rigidity, bradykinesia</td>
<td>2</td>
<td>1203</td>
</tr>
</tbody>
</table>

H&Y stage = Hoehn and Yahr stage, PD = Parkinson’s disease, L-dopa = levodopa.

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3.2. Speed of arm and trunk motions

Table 2 shows the participants’ performance in the stationary and moving ball conditions in VR and physical reality. Three-way ANOVA indicated no significant Group × Task × Context effect for any variables. For arm MT, a significant Group × Task effect was found, $F(1, 46) = 20.48$, $p < 0.001$, $\eta^2 = 0.31$, power = 0.99 (Fig. 2). Post hoc comparisons indicated that the PD group had significantly longer arm MTs than did the control group in physical reality stationary ($p < 0.001$), VR stationary ($p < 0.001$), and VR moving ($p = 0.014$) ball conditions. In both VR and physical reality, the PD group had significantly shorter arm MTs in the moving ball condition than in the stationary ball condition ($p < 0.001$).

For trunk MT, a significant context effect was found, $F(1, 46) = 10.31$, $p = 0.002$, $\eta^2 = 0.18$, power = 0.88 (Fig. 3). Trunk MT was significantly longer in physical reality than in VR. In addition, a significant group × task effect was found, $F(1, 46) = 12.49$, $p = 0.001$, $\eta^2 = 0.21$, power = 0.93. Post hoc analyses showed that the PD group had significantly longer trunk MTs than the controls when reaching for real and virtual stationary balls ($p < 0.001$). In both VR and physical reality, the PD

---

Table 2
Descriptive statistics for experimental conditions.

<table>
<thead>
<tr>
<th></th>
<th>Physical reality</th>
<th>Virtual reality</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Stationary ball</td>
<td>Moving ball</td>
</tr>
<tr>
<td>Trunk MT (s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PD</td>
<td>1.17 ± 0.24</td>
<td>0.85 ± 0.11</td>
</tr>
<tr>
<td>Control</td>
<td>0.91 ± 0.17</td>
<td>0.80 ± 0.05</td>
</tr>
<tr>
<td>Arm MT (s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PD</td>
<td>0.81 ± 0.18</td>
<td>0.60 ± 0.09</td>
</tr>
<tr>
<td>Control</td>
<td>0.59 ± 0.13</td>
<td>0.60 ± 0.06</td>
</tr>
<tr>
<td>Onset interval (s)</td>
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<td></td>
</tr>
<tr>
<td>PD</td>
<td>0.21 ± 0.12</td>
<td>0.06 ± 0.07</td>
</tr>
<tr>
<td>Control</td>
<td>0.16 ± 0.08</td>
<td>0.03 ± 0.02</td>
</tr>
<tr>
<td>Offset interval (s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PD</td>
<td>0.17 ± 0.06</td>
<td>0.19 ± 0.06</td>
</tr>
<tr>
<td>Control</td>
<td>0.17 ± 0.04</td>
<td>0.18 ± 0.07</td>
</tr>
<tr>
<td>Desynchrony score</td>
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<td></td>
</tr>
<tr>
<td>PD</td>
<td>0.32 ± 0.09</td>
<td>0.29 ± 0.09</td>
</tr>
<tr>
<td>Control</td>
<td>0.35 ± 0.07</td>
<td>0.26 ± 0.08</td>
</tr>
</tbody>
</table>

Values are mean ± SD, MT = movement time, PD = Parkinson’s disease.

Fig. 2. Group × Task × Context interaction plot (mean ± SEM) for arm movement time. CT = controls; PD = Parkinson’s disease.
and control groups had shorter trunk MTs when reaching for the moving ball than when reaching for the stationary ball (PD: \( p < 0.001 \) for VR and physical reality; control: \( p = 0.002 \) for VR, \( p = 0.008 \) for physical reality).

### 3.3. Trunk–arm coordination

Three-way ANOVA showed a significant task effect on onset interval, \( F(1, 46) = 124.10, p < 0.001, \eta^2 = 0.73 \), power = 1.00 (Fig. 4). The moving ball condition induced significantly shorter onset intervals than did the stationary ball condition. Onset intervals in the PD group were only marginally significantly longer than those in the control group, \( F(1, 46) = 3.74, p = 0.059, \eta^2 = 0.08 \), power = 0.47. Regarding offset interval, a significant Group \( \times \) Context effect, \( F(1, 46) = 5.93, p = 0.019, \eta^2 = 0.11 \), power = 0.66 (Fig. 5) and a significant Task \( \times \) Context effect, \( F(1, 46) = 16.76, p < 0.001, \eta^2 = 0.27 \), power = 0.98, were found. Further analyses showed that both groups had significantly shorter offset intervals in VR than in physical reality when reaching for moving balls (PD: \( p < 0.001 \), control: \( p = 0.031 \)). Moreover, the PD group had significantly shorter offset intervals than did the control group when reaching for the virtual moving ball (\( p = 0.031 \)).

For the desynchrony score, a significant task effect was found, \( F(1, 46) = 41.44, p < 0.001, \eta^2 = 0.47 \), power = 1.00 (Fig. 6). The moving ball condition induced lower desynchrony scores than did the stationary ball condition. In addition, a significant Group \( \times \) Context effect was found, \( F(1, 46) = 6.91, p = 0.012, \eta^2 = 0.13 \), power = 0.73. The PD group had significantly lower desynchrony scores than did the control group in VR (\( p = 0.022 \) for stationary, \( p = 0.026 \) for moving ball). When reaching for the moving ball, the PD group had significantly lower desynchrony scores in VR than in physical reality (\( p < 0.001 \)).

### 4. Discussion

We examined the temporal control of trunk and arm motions in people with PD when reaching for stationary and moving targets in VR and physical reality. Our hypotheses were generally supported. First, we found that, for people with PD, moving targets in both VR and physical reality increased the speed and synchronization of trunk and arm motions, as reflected in decreased trunk and arm MTs, onset intervals, and desynchrony scores. In addition, VR and physical reality induced different movement patterns in people with PD when they reached for moving targets, as reflected in shorter trunk MTs, shorter offset intervals, and lower desynchrony scores in VR than in physical reality.

Generally the results of the moving ball conditions confirm previous findings (Ma et al., 2011; Wang et al., 2011) that visual motion stimuli were effective for decreasing arm MT. Studies (Bärtels, Zeki, & Logothetis, 2008; Moutoussis & Zeki, 2008) have identified cortical areas in humans that respond selectively to rapid visual motion cues. It has been suggested (Majsa et al., 1998, 2008; Schenk et al., 2003) that the visual motion stimuli of moving targets engage neural circuits that are less affected by PD, and thus allow people with PD to make faster movements. Using a trunk-assistedprehension task in the present study, we found that moving targets also decreased trunk MTs, onset intervals, and desynchrony scores in both VR and physical reality. Our study extends previous findings by showing that moving targets improved not only the speed of arm movement, but also the speed of trunk movement, as well as the synchronization of trunk and arm motions, in people with PD.

Regarding the context effect, we found non-significant differences in arm MTs between VR and physical reality. The results are in line with the findings of Kuhlen et al. (2000), who reported that when reaching to grasp stationary objects, healthy adults had similar MTs in VR and physical reality, but not with those of Viau et al. (2004), who reported that healthy adults and individuals with stroke had longer MTs in VR than in physical reality. Kuhlen et al. used a 3D display for VR with no haptic feedback, which is similar to our study, while Viau et al. used a 2D display with haptic feedback. These findings suggest that a 3D display with some depth perception to indicate movement amplitude is important for arm MT.

We also found shorter trunk MTs and offset intervals in VR than in physical reality. The results of trunk MTs seem to be consistent with Knaut et al. (2009), who reported that adults with stroke used...
less trunk displacement during pointing movements in VR than in physical reality. The shorter trunk MTs and offset intervals in VR suggest that the trunk probably decelerates and stops abruptly in VR when the hand catches the target, rather than gradually decelerating and stopping, which is natural in physical reality.

The effect of context on trunk MTs and offset intervals may be attributable to differences in the participant’s perception of the target location in space (Knaut et al., 2009). The importance of vision in the synchronization of trunk and arm motions in people with PD, especially in the later phase of the movement, has been reported (Poizner et al., 2000). In addition, it has been proposed (Adamovich et al., 2001; Ma & Feldman, 1995) that, as a compensatory strategy, sensory feedback (e.g., visual, haptic) about the performance is transmitted back to arm and trunk muscles to coordinate the subsequent movement. Therefore, the insufficient depth perception and lack of haptic feedback in VR may make
Examining trunk–arm coordination provides insight into the motor control mechanism. It has been proposed (Berret, Bonnetblanc, Papaxanthis, & Pozzo, 2009) that in reaching for targets beyond arm’s length, trunk and arm motions can be controlled as one single or two distinct modules, depending on the task demand. Our findings support a flexible modular organization able to integrate or dissociate, if necessary, trunk and arm controls. For the onset interval, only a significant task effect was found, which suggested that the initiation of trunk and arm movements in people with PD can be controlled and triggered by the visual motion stimuli as one single module, as in healthy controls, regardless of whether the environment is virtual or real. In contrast, the substantial difference in offset intervals between VR and physical reality suggests that the trunk and arm are controlled separately in response to the participants uncertain about whether or not they have caught the target, especially when reaching for the moving ball. Thus, the participants may suddenly freeze the trunk immediately after the arm stops, to wait for the VR feedback about whether they have caught the ball.

Fig. 5. Group × Task × Context interaction plot (mean ± SEM) for offset interval. CT = controls; PD = Parkinson’s disease.

Fig. 6. Group × Task × Context interaction plot (mean ± SEM) for desynchrony score. CT = controls; PD = Parkinson’s disease.

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to the environmental constraint. It is likely that with the goal of catching the target, the participants
give priority to the arm control and thus decouple trunk and arm motions in VR due to the uncertainty
of target location, rendering an abrupt termination of trunk movement.

With respect to the group difference, we found that although the participants with PD had longer
trunk MTs and arm MTs than did the controls in some of the conditions, their trunk–arm coordination
was not necessarily less synchronized than that of the controls. Poizner et al. (2000) and Wang et al.
(2006) reported longer onset intervals in people with PD than in controls despite various task con-
straints (e.g., different reach speeds, object sizes, and movement amplitudes). Our finding that the
PD group had only marginally significantly longer onset intervals than did the control group may
be attributable to the use of moving targets, which attenuated the difference between the PD and con-
trol groups.

The effect of moving targets, however, is context-dependent. We found that the PD group had
shorter offset intervals and lower desynchrony scores in VR than in physical reality when reaching
for moving balls. Instead of assuming that shorter offset intervals and lower desynchrony scores repre-
sent better performance, we interpret the results as a sign suggesting that VR alters trunk–arm coordi-
adination. It appears that people with PD are more vulnerable to the limitations of VR (e.g., insufficient
depth perception) than are healthy adults when locating virtual moving targets and terminating their
movements in trunk-assisted prehension tasks. However, additional research is needed to verify this
notion.

This study has some limitations. One limitation is the design and setup of VR. The finding that VR
may alter the termination strategy of trunk and arm motions suggests the need to improve the VR sys-
tem by enhancing the sense of immersion, depth perception, and haptic feedback (Holden, 2005). It is
also important to examine whether improving the VR system will yield a more natural performance,
specifically, a termination pattern similar to that in physical reality. Another limitation was using the
same testing sequence for all participants. The participants completed the physical reality test first
and then the VR test, and in each test reached for the stationary ball first and then for the moving ball.
This testing sequence, from familiar to less familiar (VR) and from easy to difficult (the moving ball
condition), was chosen in an attempt to help participants gradually adapt to the experimental condi-
tions. It could be argued, however, that the earlier conditions may have some carryover effects on per-
formance in the later conditions. Future research should use a counterbalanced repeated-measures
design to avoid the possible carryover effect (Portney & Watkins, 2009). Finally, this study did not
use clinical measures, such as the Unified Parkinson's Disease Rating Scale (Goetz et al., 2008), to eval-
uate the functional status of the participants with PD. Including this type of information is important
in future research for generalizing the findings and making comparisons across replications.

This study has some implications. Our findings show that moving targets improve trunk and arm
movements at the same time, rather than separately. Given the known deficits of axial motor control in
people with PD (Van Emmerik, Wagenaar, Winogrodzka, & Wolters, 1999), this suggests that rehabil-
itation practitioners can use moving targets in trunk-assisted prehension tasks to improve the speed
and coordination of trunk and arm motions. On the other hand, therapists should be cautious about
using VR to provide moving targets for people with PD, because the difficulty of locating virtual mov-
ing targets may alter the termination strategy of trunk and arm motions.

### 5. Conclusion

Previous research that provided real moving targets as cueing for people with PD examined only
the movement kinematics of reach and grasp. Using a trunk-assisted prehension task, we examined
the temporal control of trunk and arm motions in response to moving targets in physical reality
and VR. Our findings extend the effect of moving target cueing to trunk–arm coordination and depict
the change of movement patterns in VR. The findings provide insight into the motor control mecha-
nism by supporting a flexible modular organization able to integrate or dissociate trunk and arm con-
trols depending on task and environmental constraints. In terms of clinical implications, we suggest
using moving targets in trunk-assisted prehension tasks to improve the speed and synchronization
of trunk and arm movements. However, rehabilitation practitioners should be cautious about using

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VR to provide moving targets for people with PD because it may alter the termination strategy of trunk and arm motions. The VR system needs improved depth perception and haptic feedback; therefore, future research should examine whether improving the VR system will yield a more natural performance, specifically, a termination pattern similar to that in physical reality.

Acknowledgments

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Effects of virtual reality training on functional reaching movements in people with Parkinson’s disease: a randomized controlled pilot trial

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Abstract

Objective: To investigate whether practising reaching for virtual moving targets would improve motor performance in people with Parkinson’s disease.

Design: Randomized pretest–posttest control group design.

Setting: A virtual reality laboratory in a university setting.

Participants: Thirty-three adults with Parkinson’s disease.

Interventions: The virtual reality training required 60 trials of reaching for fast-moving virtual balls with the dominant hand. The control group had 60 practice trials turning pegs with their non-dominant hand.

Main outcome measures: Pretest and posttest required reaching with the dominant hand to grasp real stationary balls and balls moving at different speeds down a ramp. Success rates and kinematic data (movement time, peak velocity and percentage of movement time for acceleration phase) from pretest and posttest were recorded to determine the immediate transfer effects.

Results: Compared with the control group, the virtual reality training group became faster ($F = 9.08$, $P = 0.005$) and more forceful ($F = 9.36$, $P = 0.005$) when reaching for real stationary balls. However, there was no significant difference in success rate or movement kinematics between the two groups when reaching for real moving balls.

Conclusion: A short virtual reality training programme improved the movement speed of discrete aiming tasks when participants reached for real stationary objects. However, the transfer effect was minimal when reaching for real moving objects.

Keywords

Parkinson’s disease, context, cueing, motor performance, rehabilitation

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Introduction

Among the cardinal symptoms of Parkinson’s disease, bradykinesia (i.e. movement slowness) is considered to have a large negative influence on functional performance in daily life. Accumulated evidence from neurophysiological and motor behaviour research has shown that the performance of patients can be improved by external cueing. Commonly provided cues for upper extremity movement are short presentations of visual or auditory stimuli at the start of the movement.

Several studies that used rapidly moving targets as timing cueing reported that people with Parkinson’s disease reached faster when rapidly moving targets were provided than when they reached as fast as possible for stationary objects. It has been suggested that a rapidly moving target requires that the person reaching for it must not only initiate but also properly time the movement, and thus is more effective than single cueing that primarily prompts the person to begin the movement. Because daily life is filled with tasks that require rapid and discrete aiming movements, interventions to increase movement speed are important for people with Parkinson’s disease.

With the advance of technology, virtual reality has been viewed as a potential alternative therapy for motor rehabilitation. It enables therapists to create a synthetic environment with precise control, which allows easy modification of the task to make the challenge just right for each participant. In addition, virtual reality offers repetitive practice, feedback about performance, and motivation to endure practice, all of which are important for successfully learning a motor skill. However, virtual reality also has disadvantages. Its insufficient depth perception and lack of haptic feedback may cause difficulty for participants when performing virtual reality tasks. In addition, learning novel arbitrary associations between vision and action in virtual reality requires efficient sensory processing and integrating visual and proprioceptive inputs, which may be problematic for people with Parkinson’s disease, who have been reported to have deficient sensorimotor integration mechanisms.

Therefore, given the advantages and disadvantages of virtual reality, the purpose of this study was to test whether virtual reality training would help people with Parkinson’s disease improve their functional reaching movements. To the best of our knowledge, there are no published studies on using virtual reality to train upper extremity movement in people with Parkinson’s disease. Therefore, we decided to start with a single task rather than a combination of several tasks in the virtual reality programme in order to first delineate the effect of virtual moving targets. We hypothesized that the participants with Parkinson’s disease who practised reaching for virtual moving targets would perform better (i.e. have a higher success rate and faster movement) when reaching for real stationary and moving objects than those who had engaged only in placebo training.

Methods

Participants

We enrolled a sample of convenience composed of 33 people with Parkinson’s disease. The University Hospital Institutional Review Board approved this study, and all participants signed an informed consent form before the experiment began. Inclusion criteria were (1) diagnosed with idiopathic Parkinson’s disease, (2) at modified Hoehn & Yahr stages II and III, (3) between 50 and 75 years old, (4) stable medication use, (5) no serious cognitive deficits (scored ≥24 on the Mini-Mental Status Examination), (6) normal or corrected-to-normal vision and hearing, and (7) right-handed by self-report. Exclusion criteria were (1) neurological conditions other than Parkinson’s disease or (2) musculoskeletal disorders affecting arm movement. The modified Hoehn & Yahr Scale (range: I–V) was used to evaluate the severity of Parkinson’s disease: I = mild and V = severe.
**Apparatus**

A three-dimensional electromagnetic motion tracking system (Patriot; Polhemus Inc., Colchester, VT, USA) was used to record movement kinematics. Two sensors were used: one attached to the sternum and the other to the dorsal surface of the right hand. The sampling rate was 30 Hz and latency was less than 18 ms for both sensors simultaneously. In addition, a projection-based virtual reality system connected to the Patriot was used to provide the virtual reality training programme. The digital data extracted from the Patriot were transformed into modelling coordinates and projected onto a large screen. To view the virtual reality world, participants wore a pair of polarized glasses, which provided immersive stereo visual input. The participants were then able to view their own hand movements in real time, and the flexion or extension of the trunk produced changes of the virtual world centred around the viewpoint, which served to immerse the participants in the virtual environment.

Because the Patriot is sensitive to metallic interference, we built our inclined ramp (length: 200 cm; height: 100 cm) out of aluminium and demagnetized stainless steel. On the left side of the ramp, we placed a barrier that enabled the experimenter to release the ball from behind the barrier and to control its velocity (or target viewing time) by changing the point from which the ball was released. A contact zone (10 cm long) was marked at the right terminal end of the ramp, and participants were required to reach and grasp the ball in the contact zone. The designation of a fixed contact zone ensured that participants grasped the ball from the same ramp location under all conditions. Based on pilot work, we inclined the ramp at a $10^\circ$ angle. From the edge of the barrier to the contact zone, the ramp was 70 cm long. Because the ball was released at different points behind the barrier, the time it took for it to appear from behind the barrier until it reached the contact zone varied: 1.1, 0.9, 0.7, and 0.5 seconds.

The virtual reality programme was designed using the following software: OpenGL (Open Graphics Library, Khronos Group, Beaverton, OR, USA), Visual C++ (Microsoft, Redmond, WA, USA), and MFC (Microsoft Foundation Class; Microsoft). A virtual ramp, identical to the aforementioned inclined ramp, except for the start position of the moving ball, was designed. In the virtual ramp, a virtual hammer was used to strike the ball and propel it into the contact zone; the amount of time between the hammer’s appearance until it struck the ball was random. The hammer was used as a warning signal because our pilot work suggested that participants usually failed to respond to the moving ball if it appeared suddenly from behind the barrier, as it did on the real ramp. In addition, to compensate for the insufficient depth perception in virtual reality, a concrete target was provided to help participants locate the virtual contact zone. The time from when the ball starting moving to when it entered the contact zone was easily manipulated by setting that time in the virtual reality programme. A trial was considered successful when the distance between the participant’s hand sensor and the centre of the ball was between 5.75 cm and 8.75 cm (the radius of the ball plus 2.5 cm and 5.5 cm, respectively) in the contact zone. When a participant successfully caught the ball, the ball would move with the participant’s hand for 2 seconds, as it would have had the participant actually lifted the ball from the contact zone.

**Design and procedures**

This study used a pretest–posttest control group design. Thirty-three participants were randomly assigned to virtual reality training or control groups by means of sealed envelopes that contained randomly filled group allocations (Figure 1).

For the pretest and posttest, the participant sat in the start position in an armless chair with their right hand resting close to the knee on their right thigh. The real inclined ramp was placed parallel to the frontal plane of the participant at a distance equal to 120% of arm length.
The height and position of the ramp was set so that the contact zone was in front of the right shoulder at chest level. For the testing, the participant was required to reach and grasp a tennis ball (6.5 cm in diameter) with the right hand under five conditions: the ball was stationary in one condition and moving in four. In the stationary condition, the ball was placed in the contact zone, where it remained stationary. The participant was required to reach as fast as possible to grasp the ball. In the four moving conditions, the ball was rolled from behind a barrier, left-to-right down the inclined ramp, and through the contact zone. The participant was required to reach and grasp the moving ball from within the contact zone. The stationary ball test was done first and then, in random order, the moving ball tests. The participants were allowed one practice trial and five test trials under each test condition. Kinematic data from the practice trials were not included in the analysis.

For the virtual reality training group, the participant sat in the same place as in the pretest. The virtual reality world was adjusted to locate the virtual contact zone (also indicated by a concrete target) in front of the participant at a distance of 120% of arm length at chest level, just as in the pretest task setup. The participant was required to reach for 60 virtual moving balls with the right hand and was allowed to take a rest whenever needed. The speed of the virtual moving ball to be reached for was the fastest speed in the pretest at which the participant achieved more than 60% success. The number of training trials was decided based

Figure 1. Flow diagram of the study.
on our pilot study, in which we wanted to allow the participants a certain amount of practice reaching for the ball, and yet not become tired. The training took about 10 minutes to complete, which was about the duration of an activity in a typical occupational therapy session. Only one participant complained about fatigue and took a 3-minute break during the virtual reality training.

Because the effect of such a virtual reality training programme has not been established in previous research, we decided to give the control group placebo training, during which participants used their left hand to turn 60 wooden cylinders at a self-placed speed. We assumed that the placebo training would not have any effect on the right hand, and thus, we hypothesized, the effect of virtual reality training would be totally reflected in the difference in right-hand performance between the two groups. Five minutes after the virtual reality or control training, the participants took the post-test. The entire experiment took about 1 hour to complete.

Data reduction and analysis

The pretest and posttest success rates for the moving ball conditions were computed. A trial was considered successful if the participant touched and stopped the moving ball in the contact zone. For kinematic measures, the position series were used for velocity computation and digitally filtered using the moving-average filter. The cut-off value to define movement onset and offset was set at 5% of peak velocity.

This study included the following kinematic variables of arm movement: movement time, amplitude of peak velocity, and percentage of movement time for the acceleration phase. Movement time is the duration of the execution of an arm movement. A faster movement has a shorter movement time.\textsuperscript{25,26} Peak velocity is the highest instantaneous velocity during the arm movement. The higher the peak velocity, the more forceful the movement.\textsuperscript{26–28} When the hand reaches for a target, it generally first accelerates toward the target and then decelerates to correct the trajectory. It is believed that the acceleration phase is associated with the initial projection of movement forces,\textsuperscript{29} and that the deceleration phase is used to process feedback information and to adjust movement trajectory.\textsuperscript{30,31}

A mixed two-way analysis of variance (ANOVA) with one between factor (group: virtual reality versus control) and one within factor (time: pretest versus posttest) was used to analyse participant performance when they reached for stationary balls. A mixed three-way ANOVA with an additional within factor (moving ball speed in terms of the time constraint: 1.1 versus 0.9 versus 0.7 versus 0.5 seconds) was used to analyse participant performance when they reached for moving balls.

Results

Seventeen participants were randomly assigned to the virtual reality training group and 16 to the control group (Figure 1). The demographic and clinical characteristics of the two groups were comparable (Table 1). Most of the participants were at modified Hoehn & Yahr stage II, meaning that their symptoms were bilateral and that they had minimal disability.\textsuperscript{22}

In the stationary ball condition, all participants successfully grasped the ball (Table 2). Two-way ANOVA indicated a significant time effect on movement time and a significant group × time interaction effect on movement time and peak velocity. Specifically, in the virtual reality group, movement time decreased and peak velocity increased from pretest to posttest, while in the control group, movement time was similar and peak velocity decreased from pretest to posttest.

For the moving ball conditions, three-way ANOVA showed that the speed of the moving ball significantly affected the success rates and kinematic performance for all participants: as the ball moved faster, success rates became lower (\textit{F}(3,93) = 33.19, \textit{P} < 0.001), movement time shorter (\textit{F}(3,90) = 193.46, \textit{P} < 0.001), peak
velocity higher \( F(3,90) = 184.13, \ P < 0.001 \), and percentage of movement time for acceleration lower \( F(3,90) = 6.91, \ P < 0.001 \). However, there was no significant effect related to the group, such as a group \( \times \) time or a group \( \times \) time \( \times \) cueing effect. Table 3 shows participants’ pretest and posttest performance when reaching for moving balls. Effect size \( d \) was calculated to determine the magnitude of change between pretest and posttest values for the virtual reality and control groups under each moving ball condition. A \( d \) of 0.2 suggests a small effect, 0.5 a medium effect, and 0.8 a large effect.\(^\text{32}\) Although the group effects were not significant, a further examination of effect size suggested that under the same moving ball condition, the effects of virtual reality training on most kinematic variables were slightly larger than the effects of control training, especially in the fast (0.7 and 0.5 seconds) moving ball conditions.

### Discussion

Our results partially support our hypothesis. We found that virtual reality training more effectively than control training improved our study participants’ performance in reaching for real stationary balls. Those who practised reaching for virtual moving balls showed significantly decreased movement time and increased peak velocity, while the participants who received placebo training showed no significant change in movement time and a significantly reduced peak velocity from the pretest to the posttest. However, the training effect was not evident

---

**Table 1. Characteristics of study participants**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Virtual reality ((n = 17))</th>
<th>Controls ((n = 16))</th>
<th>(P)-value (two-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex ((\text{man/woman}))</td>
<td>8/9</td>
<td>10/6</td>
<td>0.601</td>
</tr>
<tr>
<td>Age ((\text{years}))</td>
<td>64.77 ± 8.47</td>
<td>68.13 ± 7.38</td>
<td>0.235</td>
</tr>
<tr>
<td>Modified H&amp;Y stage ((\text{II/III}))</td>
<td>16/1</td>
<td>13/3</td>
<td>0.258</td>
</tr>
<tr>
<td>Disease duration ((\text{years}))</td>
<td>5.32 ± 4.43</td>
<td>5.16 ± 3.43</td>
<td>0.906</td>
</tr>
<tr>
<td>MMSE</td>
<td>27.24 ± 3.09</td>
<td>26.31 ± 2.52</td>
<td>0.357</td>
</tr>
</tbody>
</table>

Values are means ± SD.

H & Y, Hoehn & Yahr; MMSE, Mini-Mental Status Examination.

**Table 2. Effects of virtual reality training in the stationary ball condition**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Test</th>
<th>Group</th>
<th>Group effect</th>
<th>Time effect</th>
<th>Group ( \times ) time effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>MT ((\text{seconds}))</td>
<td>Pretest</td>
<td>0.79 ± 0.17</td>
<td>0.78 ± 0.20</td>
<td>0.94</td>
<td>0.340</td>
</tr>
<tr>
<td></td>
<td>Posttest</td>
<td>0.67 ± 0.15</td>
<td>0.79 ± 0.18</td>
<td>0.05</td>
<td>0.818</td>
</tr>
<tr>
<td>PV ((\text{cm/s}))</td>
<td>Pretest</td>
<td>147.55 ± 31.37</td>
<td>159.63 ± 36.17</td>
<td>0.05</td>
<td>0.829</td>
</tr>
<tr>
<td></td>
<td>Posttest</td>
<td>166.84 ± 36.58</td>
<td>149.33 ± 40.50</td>
<td>0.39 ± 0.08</td>
<td>0.41 ± 0.09</td>
</tr>
</tbody>
</table>

Values are means ± SD.

MT, movement time; PV, peak velocity; PTA, percentage of movement time for the acceleration phase.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Test</th>
<th>1.1 s</th>
<th>0.9 s</th>
<th>0.7 s</th>
<th>0.5 s</th>
<th>1.1 s</th>
<th>0.9 s</th>
<th>0.7 s</th>
<th>0.5 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Success rate</td>
<td>Pretest</td>
<td>0.96 ± 0.08</td>
<td>0.98 ± 0.10</td>
<td>0.94 ± 0.12</td>
<td>0.60 ± 0.34</td>
<td>1.00 ± 0.00</td>
<td>0.98 ± 0.07</td>
<td>0.93 ± 0.14</td>
<td>0.79 ± 0.24</td>
</tr>
<tr>
<td></td>
<td>Posttest</td>
<td>0.99 ± 0.05</td>
<td>0.99 ± 0.05</td>
<td>0.91 ± 0.17</td>
<td>0.66 ± 0.37</td>
<td>0.99 ± 0.05</td>
<td>1.00 ± 0.00</td>
<td>0.98 ± 0.07</td>
<td>0.79 ± 0.26</td>
</tr>
<tr>
<td>Effect size d</td>
<td>Pretest</td>
<td>0.37</td>
<td>0.16</td>
<td>-0.24</td>
<td>0.17</td>
<td>-0.50</td>
<td>0.73</td>
<td>0.47</td>
<td>0.00</td>
</tr>
<tr>
<td>MT (s)</td>
<td>Posttest</td>
<td>0.83 ± 0.10</td>
<td>0.77 ± 0.09</td>
<td>0.60 ± 0.08</td>
<td>0.46 ± 0.06</td>
<td>0.78 ± 0.08</td>
<td>0.73 ± 0.11</td>
<td>0.61 ± 0.11</td>
<td>0.45 ± 0.07</td>
</tr>
<tr>
<td>Effect size d</td>
<td>Pretest</td>
<td>0.05</td>
<td>0.40</td>
<td>0.15</td>
<td>0.18</td>
<td>0.21</td>
<td>0.13</td>
<td>-0.09</td>
<td>0.00</td>
</tr>
<tr>
<td>PV (cm/s)</td>
<td>Posttest</td>
<td>124.4 ± 21.5</td>
<td>137.6 ± 22.2</td>
<td>164.5 ± 35.2</td>
<td>217.6 ± 36.0</td>
<td>133.7 ± 20.1</td>
<td>141.1 ± 25.0</td>
<td>164.4 ± 21.5</td>
<td>229.0 ± 34.5</td>
</tr>
<tr>
<td>Effect size d</td>
<td>Pretest</td>
<td>0.10</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
<td>-0.13</td>
<td>-0.08</td>
<td>-0.27</td>
<td>-0.22</td>
</tr>
<tr>
<td>PTA (%)</td>
<td>Posttest</td>
<td>0.55 ± 0.17</td>
<td>0.50 ± 0.16</td>
<td>0.47 ± 0.11</td>
<td>0.47 ± 0.12</td>
<td>0.54 ± 0.13</td>
<td>0.52 ± 0.09</td>
<td>0.50 ± 0.12</td>
<td>0.49 ± 0.08</td>
</tr>
<tr>
<td>Effect size d</td>
<td>Pretest</td>
<td>0.16</td>
<td>-0.05</td>
<td>0.51</td>
<td>0.37</td>
<td>0.09</td>
<td>-0.15</td>
<td>0.01</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Values are means ± SD.

MT, movement time; PV, peak velocity; PTA, percentage of movement time for the acceleration phase.
for either group when reaching for real moving balls. A close look at the data suggests that although the virtual reality group participants did not have a higher success rate than the control group participants, they slightly improved or else maintained their kinematic performance, while the control group participants either showed no change or else slightly declined in kinematic performance from the pretest to the posttest. Overall, the results suggest that virtual reality training may improve movement speed, as was reflected in the kinematic performance of reaching for stationary balls. These results are in line with previous findings, which reported that people with Parkinson’s disease who practised improved their speed on discrete and sequential targeting tasks and retained the improvement after a 10-minute retention test interval.

However, the success rate results suggest that our virtual reality training did not help the participants improve their visuomotor coordination when reaching for moving objects. These results may be attributed to task difficulty, context difference and practice conditions. Catching moving balls is more demanding on the participant’s visuomotor processing and movement execution than is catching stationary balls. The challenge of catching fast-moving balls is further complicated by the difference between virtual reality and physical reality. Previous research has reported that people with Parkinson’s disease experienced modest difficulty when transferring the improvement from initial learning to a new context. Accordingly, because the visuomotor coordination pattern practised in the virtual reality training was somewhat different from that required for the posttest, the virtual reality group participants did not significantly improve their performance when reaching for real moving balls. For future research, we suggest including a warm-up phase in the posttest test to help participants adjust to physical reality.

Finally, regarding the practice conditions, the consistent speed of fast-moving balls during the virtual reality training may have facilitated faster arm movement, but the lack of speed variation in practice probably prevented the participants from learning how best to vary their movements in response to the changing speeds of the moving balls in the posttest. Lin et al. reported that people with Parkinson’s disease who engaged in blocked practice retained the practised skills better than those who engaged in random practice. They used a retention test, in which participants were tested with the same task they had practised. The posttest in our study, however, was a transfer test, in which participants performed the previously learned task in a novel situation. Comparing the effects of blocked versus random practice may result in different findings depending on whether retention or transfer tests are used. Therefore, we recommend that future research include random practice, in which participants reach for objects moving at various speeds, to test whether such training improves not only movement speed, but also visuomotor coordination.

For the moving ball conditions, we found a significant effect of cueing (moving ball) speed. The movement of all participants became faster and more forceful as the ball moved faster. These results support previous findings on the effect of moving target objects in people with Parkinson’s disease. Previous research focuses on immediate motor performance at different cueing speeds, rather than on examining the long-term effect of cueing speed on performance change. In our study, the effect of cueing speed was even larger than the effect of a short virtual reality training session. Therefore, it is important for future research to use moving targets for training and to examine their long-term effect on both movement speed and visuomotor coordination in people with Parkinson’s disease.

It is important to design virtual reality training programmes according to the characteristics and needs of the target population. Many virtual reality programmes designed for people with hemiparesis are aimed at improving their motor control, strength and dexterity, and they emphasize accuracy more than speed. For people with Parkinson’s disease, virtual reality
programme designers should take advantage of rapidly moving targets to improve participants’ motor response and to emphasize movement speed in order to counteract symptomatic movement slowness. Moreover, to optimize the learning effect, it is important to modify task difficulty according to the participant’s success rate and motor performance. In physical reality, manipulating target speed and viewing time requires many trials and modifications of the apparatus, such as changing the target starting point or the ramp inclination angle. In contrast, the virtual reality system allows easy manipulation and precise control once the programme has been developed. By using a single task that provided virtual moving targets, we showed evidence that such a training task, which was practised only briefly and only once, can improve the movement speed of people with mild-to-moderate Parkinson’s disease. Our findings support the future development of other virtual reality programmes that include moving targets to provide various dynamic and interesting activities for people with Parkinson’s disease.

This study has some limitations. First, the practice session was short in this pilot study. The limited practice duration (60 practice trials) might have compromised motor learning in our participants. Future work should provide more extensive virtual reality training and allow participants to practise reaching for objects moving at various speeds. In addition, we assessed the immediate transfer effect of virtual reality training with a short break between the practice session and the posttest. In view of the difficulty for people with Parkinson’s disease to switch between different contexts, future research probably should include a warm-up phase in the transfer test to help participants adjust to the real context. Longer follow-up periods will also be necessary to determine the relatively permanent changes induced by virtual reality training. Moreover, for the virtual reality system, improvements (e.g. a head-mounted display, a haptic glove) may be needed to increase the participants’ sense of immersion, depth perception, and haptic feedback. We believe, however, that even with the most advanced virtual reality equipment, the gap between virtual and physical reality cannot be easily closed because of the complex and delicate visual perceptual functions in humans, such as accommodation, vergence, and motion parallax. Therefore, future research should try to identify key characteristics of virtual reality tasks that elicit visuomotor coordination and interactive behaviour as natural as that in physical reality.

The operational definition of a control condition is important to the interpretation of outcomes. The placebo training for the control group was designed to control for the effects of confounding factors, such as time and attention, but not to lead to changes in their right-hand performance, which was the outcome measured in this study. Based on our findings that practising reaching for virtual moving balls improved performance more than did no practice, further research may evaluate practising reaching for virtual moving balls against practising reaching for real moving balls to determine whether practising in virtual reality is more effective than practising in physical reality.

Our findings have implications for training people with mild-to-moderate Parkinson’s disease. Because more clinics now use virtual reality equipment for motor rehabilitation, therapists need to be aware of its benefits and limitations. Our results suggest that practising fast movement in virtual reality can be generalized to fast reaching for stationary objects in physical reality, but not to reaching for moving objects, because the visuomotor coordination patterns involved are somewhat different between virtual reality and physical reality. Additional research is needed to examine whether more extensive virtual reality training with targets that move at different speeds helps people with Parkinson’s disease improve the speed of their motor performance as well as their visuomotor coordination. In addition, fast-moving targets are effective for increasing movement speed in people with Parkinson’s disease. We recommend that
therapists include catching fast-moving targets in treatment activities and that they vary the target speed to provide opportunities for practicing fast movement and efficient visuomotor coordination.

**Clinical messages**

- Fast moving targets are effective for increasing movement speed, but not success rate, in people with Parkinson’s disease.
- Practising reaching for fast-moving virtual targets improves the movement speed of reaching for real stationary objects in people with Parkinson’s disease.

**Contributors**

HIM participated in virtual reality system design, study design, data analysis, and initial manuscript preparation and revision. WJH participated in study design, subject recruitment, data collection, data analysis, and manuscript revision. JKF participated in virtual reality system design and manuscript revision. JKK participated in virtual reality system design, data collection, and manuscript revision. CYW participated in study design, data collection, data analysis, and manuscript revision processes. IFL participated in virtual reality system design and revision, and manuscript revision. TYW participated in study design, data analysis, initial manuscript preparation and revision. All authors read and approved the final manuscript.

**Competing interests**

None declared.

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